DISCUSSION BEFORE THE WIRELESS SECTION, 24TH FEBRUARY, 1932.

Mr. N. Ashbridge: Since the selectivity of receivers is closely associated with the performance of broadcast transmitters, the subject of selectivity is of great importance to the British Broadcasting Corporation. The first question I wish to discuss is the demand for selective receivers on the part of the public. We may divide the public into two classes: in the first class there are those who live in an area of strong field strength of upwards of 20 millivolts per metre, where selectivity is not particularly necessary because very little interference from other sources is noticeable. In the second class there are those who live in an area where the signal strength is about 5 millivolts per metre, and who might reasonably expect good reception were it not for interference due to peaks of signal strength from a distant station at night. At times the two stations may be of equal field strength and only 9 kilocycles per sec. apart in frequency. It is often suggested that the B.B.C. ought to cut off the higher frequencies at the transmitter. Apart from the effect that the adoption of this suggestion

would have on what we call " side-band heterodyning," if we were to cut off at, say, 5 000 cycles per sec. the masses of people living in areas of strong field strength would have reason to complain of the inferior quality of the transmissions. In this connection one has to consider what frequencies from the interfering station cause the " grasshopper " kind of noise which we call side-band heterodyning. I think this noise is due not to the extremely high frequencies but to those where the energy is the greatest, i.e. frequencies of 1 000 to 2 000 cycles per sec. It is therefore questionable whether, if the higher frequencies were deliberately cut off in the transmitter, there would be much reduction of these noises. With regard to highly selective receivers, one of the first essentials is stability of tuning. Unless care is taken in the design of a mains receiver the tuning will vary with every change in the mains voltage. Even in the case of transmitters a greater degree of stability is desirable if we are to use the extreme degree of selectivity which has been discussed lately. Prof. Fortescue has stated that the range of musical frequencies which ought to be included is 50 to 5 000 cycles per sec., and although I am in agreement with him here I consider that sooner or later higher frequencies will have to be considered. Recording by the " hill and dale " method in America deals with frequencies up to about 9 000, and this may tend to accentuate the demand for higher frequencies. On the other hand, a large number of our programmes are transmitted over Post Office circuits, some of which cut off at just over 6 000 cycles per sec., and of course this prevents the transmission of the higher frequencies in some cases. With regard to the judging of quality by musical people, we notice that a musician, no matter how good he may be, is not particularly sensitive to the width of the frequency band included in the transmission. He is, however, very sensitive to changes in amplitude, i.e. bad modulation control. On the other hand, people who are not musicians but who are interested in musical reproduction will at once notice if one cuts off frequencies above 5 000 cycles per sec. I believe this class of listener is very numerous nowadays. The public in general do notice the difference between the frequency cut-off of 5XX and that of the new transmitters. Even at 5 000 cycles per sec. the response of 5XX is reduced by at least 8 or 10 decibels. In addition, many receivers cut off seriously on the long wavelength employed by 5XX. As regards the upper limit for loud-speakers, I think 2 000 cycles per sec. is rather pessimistic for the average receiver in use to-day. Many modern loud-speakers register well above 5 000 cycles per sec., and although the response may be hopelessly non-linear at this frequency the fact that some sound is produced is more important than the maintenance of an exact mathematical relation to the response at other frequencies. Turning to the question of the spacing which should be allowed between the frequency channels of broadcasting stations, I should like to draw attention to the fact that the London Regional transmitter works at a frequency which differs by 11 kilocycles per sec. from that of its troublesome neighbour, and the frequency of the North Regional transmitter is roughly 11 kilocycles per sec. different from those of the Langenberg and Prague stations. Because these are free from interference, however, it is not necessarily correct to say that the present standard spacing of 9 kilocycles per sec. is quite adequate. We are very interested in single side-band working, i.e. transmitting one side-band with the carrier but not the other. To derive any considerable advantage from this system one would presumably have to cut off one side-band in the receiver. If the whole of Europe decided to change over to single-side-band working (and one day they may do so), each of the 12 million licensed receivers in Europe would have to be provided with a filter which would cut off one side-band completely. Such a filter could certainly not be produced for less than £1, and therefore, apart from the technical difficulties, the change-over to the new system would be exceedingly costly. Finally, I want to say something about the position abroad with regard to the frequency separation between stations. Many broadcast engineers abroad are not very concerned about frequencies over 4 000, and the type of receiver which they consider suitable for working in a country district is designed to cut off almost completely at 4 000 to 4 500 cycles per sec. in order to give interference-free reception. Foreign radio engineers do not complain of side-band heterodyning from our stations, whereas in England we get numerous complaints of side-band heterodyning even when there is an 11-kilocycle separation. There are two reasons for this state of affairs. In the first place, ultra-selective receivers are used abroad, and secondly (this is much more important) other countries employ a much higher mean modulation than we do. Modulation records which we have taken recently on certain Continental stations show that their mean modulation may be double ours. I consider that in the future there will be a demand for higher modulation frequencies: we should be able to receive on a loud-speaker much higher frequencies than 4 500 or 5 000, and I therefore feel that we must seriously consider the question of a wider frequency separation between stations. In this connection it is interesting to note that the United States consider that the broadcast cables now being put down should have a linear response up to 8 000 cycles per sec.

Mr. P. K. Turner: Prof. Fortescue makes the implication that the talking film sets a higher standard than broadcast reception in the matter of the upper frequency limit, whereas my experience of both gramophone recording and talking-film making, and, from the receiving end, of broadcast transmission, proves to me that the reverse is the case. My experience is that a clear cut-off at 5 000 cycles per sec. is regarded as a luxury in gramophone or talking-film recording, whereas we know that broadcast transmission contains at least another octave above that frequency. Prof. Fortescue is of opinion, and in strict logic I think he is perfectly correct, that in any attempt to estimate the performance of radio receivers one must include the performance of the loud-speaker. Unfortunately the practicability of this is very doubtful, because even if one includes in the performance curve of the receiver the mean spherical radiation of the loud-speaker, one cannot make any allowance for the acoustic circumstances in which it is being used. It is not only that the set must include one particular loud-speaker and no other, but it must be used in one particular type of room and no other; otherwise the

curve cannot be guaranteed. A sounder procedure is to base all our considerations on getting the best possible receiver, and to leave as a separate problem the selection of the best loud-speaker by suitable impedance matching. Again, according to Prof. Fortescue, strict mathematical logic implies that if a stray side-band from an unwanted transmission cuts into the band we are trying to receive, the results must be the same as if this wave had been a side-band of the desired transmission. I am not entirely convinced about this, because there is the difference that what we wish to receive consists of two side-bands, on each side of the carrier and having a definite phase-relation with it, whereas the unwanted radiation consists of one side-band only, its carrier and other side-band being possibly cut out by the receiver. Therefore we cannot say that the stray side-band must necessarily be identical in behaviour with the wanted pair of side-bands. An interesting point in this connection is the " demodulation " effect, i.e. the fact that the modulation of the unwanted carrier tends to disappear when the signal strength of the latter has been reduced to not more than 1/100 of that of the wanted carrier. I have found by experiment that when a carrier 10 kilocycles per sec. from the desired transmission is reduced to 1/300 or 1/400 of the signal strength of the wanted carrier, and the audio-frequencies are then reconstituted by means of a differentiating circuit, the " grasshopper effect " is reduced to very small dimensions. In a circuit of that kind the actual carrier, the heterodyne 10-kilocycle whistle, is reconstituted at full strength and has to be dealt with specially; but this presents little difficulty. I should like to press very strongly for the retention of frequencies above 5 000 cycles per sec. There is no doubt that anyone who has a keen (but not necessarily musically trained) ear and who is not deaf to those frequencies, soon learns to appreciate the difference between a transmission with them and one without. I find that even musical people are at first satisfied with transmissions which do not contain either these frequencies or those below 100 cycles per sec., and which suffer from all sorts of defects. They sub-consciously supply what is missing and they also dispense with what ought not to be there. However, if such people hear in quick succession a good and a comparatively poor transmission, they soon learn to notice the difference and become dissatisfied. In my opinion 8 000 cycles per sec. is the lowest cut-off possible if first-class quality is to be obtained. Lastly, I should like to state that there may be difficulties as to the handling of extremely selective sets by unskilled people. First, the mechanical difficulty of adjusting to exact tuning is merely a matter of gearing. Secondly, there is the difficulty of knowing when the set is correctly adjusted—a much more difficult problem. Receivers of the kind which I have been discussing, in which a super-selective circuit is followed by tone correction, give extraordinary results if there is any error in tuning. If the set is 200 cycles per sec. off tune, strong resonance is obtained at 200 cycles per sec. and nothing at all at lower frequencies. It is therefore essential to provide some indicating device, so that the listener may tune in by adjusting until the needle on the indicator goes up and comes back again, instead of relying on his own ear.

Mr. F. S. Barton: With regard to the remarks which have been made as to the necessary frequency range, I should like to refer to some work carried out in the Bell Telephone Laboratories which has recently been published* in America. In these tests, while several experienced listeners were listening to an orchestra the low and high frequencies were cut off by varying amounts with filters. It was found that when a frequency range extending from 80 to 8 000 cycles per sec. was employed the listeners considered the reproduction to be 95 per cent perfect. The problem before the designer of a commercial radio-telephony channel is simpler than the broadcast problem, because the designer knows definitely what band he has to deal with and he has not to arrange the apparatus so that it may be operated by a layman. Further, he is not hampered by financial considerations, because increasing the cost of a commercial receiver by £50 only adds a trifle to the capital outlay on the whole channel, and if the more expensive receiver gives an improved performance it will soon show an economic return. The increasing congestion in the short-wave channel makes it necessary to use that channel as efficiently as possible, and this can best be done by means of stable transmitters and very selective receivers. At the Royal Aircraft Establishment at Farnborough we are faced with the problem of obtaining short-wave communication for the Royal Air Force despite the inroads of commerce, and in order to solve this problem we are trying to design more selective receivers. Our ultimate object is to produce receivers suitable for aircraft work, but we usually approach an aircraft problem by first considering the same problem as applied to ground communications. Inspired by the work of the Post Office Research Station at Dollis Hill, we decided to investigate the possibilities of a super-heterodyne receiver with a band-pass filter in the intermediate-frequency amplifier. By a band-pass filter in the intermediate-frequency amplifier I mean a filter designed on the Campbell and Zobel theory and working between definite impedances, and not the arrangement of two coupled circuits arranged to maintain their coupling substantially constant over the tuning range, to which the term " band-pass filter " has been wrongly applied by the broadcast receiver manufacturer. While the latter arrangement is an improvement on a single circuit, and also on a coupled circuit with adjustable coupling, it is not a band-pass filter in the strict sense of the term. I cannot understand why band-pass filters have not been more used for radio frequencies, and I should be glad of information regarding the operating characteristics of this type of filter.

Mr. M. G. Scroggie: It may clarify our ideas on the subject of the relationship between selectivity and the desirable band of audio frequencies, to refer to three practical cases. In the first case the two transmissions are completely separated and the side-bands do not overlap at all. It is universally agreed that, at any rate in theory, it is possible to separate these transmissions completely in the receiver by using a perfect band-pass filter. In the second case the side-bands overlap, and there seems still to be some controversy over the question

* W. B. Snow: *Journal of the Acoustical Society of America*, 1931, vol. 3, p. 155.

whether it is possible to obtain the whole band of frequencies due to one of the stations, at the full modulation without any heterodyne interference. In the third case the side-bands overlap the carrier waves; it is now, I think, generally agreed that it is impossible to receive one of these transmissions without interference except by losing some of the modulation. The orthodox position is that complete separation is possible only in the first case, and, as Prof. Fortescue points out, it is generally considered desirable to cover an audio-frequency band of 10 kilocycles per sec., or preferably even more. What I have great difficulty in understanding is how it is possible to reconcile these aims with the unpleasant fact that the frequencies of stations are at present, on the average, separated by 9 kilocycles per sec. It seems to me not very much use discussing, at length, principles which can have no actual application to things as they are, but which can only be applied in things as we should like them to be. Assuming the principles stated by Prof. Fortescue, even with a theoretically perfect receiver one can cover an audible range up to only 4 500 cycles per sec. In the second case to which I referred, if one tried to include an audio-acceptance up to 10 kilocycles per sec. one would include not only the wanted station but also the carrier waves of two other stations and side-band frequencies of four other stations. To obtain complete freedom from interference the highest audio frequency put out by broadcast stations and received must not exceed 4 500 cycles per sec. with theoretically perfect apparatus; which means in practice that a good receiver can be allowed to reproduce up to perhaps 3 500 cycles per sec. Only those who claim to be able to discriminate between two waves of the same frequency can indulge in any higher hopes than these. If the unwanted station puts out modulation up to 9 kilocycles per sec. it seems theoretically impossible to receive anything at all of the wanted transmission without interference. I think it would be useful if the broadcasting authorities stated exactly what the limits of audio-frequency modulation are. Even if it is possible to discriminate between wanted and unwanted side-bands it is quite idealistic to think of accepting audio frequencies up to 10 kilocycles per sec., for this value includes the neighbouring carrier wave. It would therefore be helpful to know whether it is considered better to cut off at 3 000 or 4 000 cycles per sec. in receivers of practical design, or to tolerate the interference. I would add that there are districts in this country where the field strength from the nearest British station is considerably lower than that from Continental stations, and therefore one cannot assume, even for " local-station " reception, that the field strength of the wanted station is very much greater than that of the unwanted station.

Mr. I. J. Cohen: I should like to give a rough picture of the existing conditions in commercial radio-telephony. Consider, in the first place, the long-wave transatlantic telephone service, which operates on the single-side-band suppressed carrier system. As the circuits are required for telephone use, only the frequencies corresponding to the audio-frequency band of from 250 to 2 750 cycles per sec. are considered. Over this range the response characteristic of the receiving system has to be flat to within ± 1 decibel. At present there are not many long-wave telephone circuits, so that there is no necessity to guard against interference from this source. The ether is full of long-wave telegraph transmissions, however; at 250 cycles per sec. from the carrier frequency on one side of the allotted telephony band and at 500 cycles per sec. from it on the other, there exist strong telegraph carrier frequencies. These spread slightly, the degree of spreading being dependent on the nature and speed of keying, and therefore the cut-off of the telephony receiver must be extremely sharp. As to the relative strengths of the wanted and unwanted frequencies, the field strength of the American signals may be as low as 1 microvolt per metre (the usual figure being about 25 microvolts per metre), and that of the telegraph stations about 100 microvolts per metre. An attenuation of 40 decibels is, therefore, required to bring the signals to equal strength, and then to make the telegraphy nearly inaudible another 40 decibels or more have to be added. Thus at least 80 decibels cut-off is required at 500 cycles per sec. from the edges of the received band. In this case, therefore, the ideal rectangular overall frequency characteristic mentioned by Prof. Fortescue is almost a necessity, and I maintain that such a characteristic can be obtained only with properly designed band-pass filters or their equivalent high- and low-pass sections. Referring to the multiple-detection type of receiver, provided that the early stages are properly protected against the image side-band, the intermediate-frequency band, and overloading, there can be little doubt that the overall curve of the super-heterodyne type of receiver can be made to approach the ideal characteristic more closely than the curves of other types of receivers. On the wavelengths from 14 to 40 metres conditions are now nearly as bad as on the broadcasting band. It is necessary to limit the receiving band widths of the short-wave telephony sets to between 8 000 and 9 000 cycles per sec., and to have a large degree of attenuation outside this range. The Post Office receivers used on these services contain some two dozen valves, five high-frequency tuned circuits, intermediate-frequency band-pass filters containing many sections, audio-frequency filters, and equalizers. To obtain sufficient selectivity it will perhaps be necessary to build the broadcasting receiver of the future on these lines.

Mr. P. W. Willans: One of the principal difficulties associated with a scientific treatment of selectivity problems is, as Mr. Turner has pointed out, our ignorance of the performance of loud-speakers. The acoustic problem involved in the complete circuit of transmitter and receiver comprises the polar characteristics of both the microphone and the loud-speaker, and the acoustic characteristics of both the transmitting and the receiving rooms. These considerations prevent us from taking a strictly scientific view of the subject; broadcasting is an art, not a science. We have to envisage the performer not as playing in the studio and being reproduced as faithfully as possible, but as playing in the home of the listener through the transmitting and receiving systems, which are in effect a part of his instrument. While scientific considerations are invaluable for indicating what is going on, the ultimate criterion must be one of æsthetic value. In any event it seems clear that no

precise quantitative definition of acoustic response is possible and that, in consequence, there is no satisfactory answer to Prof. Fortescue's first question. My second point is more particularly concerned with transmission. I believe that, in view of the nature of present-day broadcast transmissions, Prof. Fortescue's rectangle is not the most desirable response characteristic for a receiver. Most microphones, including the condenser and carbon types used by the B.B.C., give a rising characteristic in the neighbourhood of 3 000 cycles per sec. In the case of condenser microphones this rise in response may amount to 12 decibels at 3 000 cycles per sec. as compared with the response at low frequencies, if the sound is normally incident on the diaphragm. For random incidence this " top " accentuation will not be so heavy, the corresponding rise in response for a condenser microphone being about 7 decibels. As a result of some experience obtained in adjusting the response characteristic of a sensitive receiver, I am fairly certain that the present transmissions are in general too " toppy," and that a receiver designed to have a flat band-pass characteristic will be incorrectly adjusted for best results. I believe it is possible to cut out the higher frequencies without detriment to quality, and this is the only way in which the problem of lessening carrier-wave interference can be tackled. My only fear is that the B.B.C., realizing the situation, may suddenly decide to transmit on a flat response characteristic, in which case listeners would probably find their reproduction lacking in " top." I hope that the B.B.C. will pursue their investigations into the subject of microphones, with a view to eliminating sound-field effect and producing an exact translating device, and that they will consider accentuating the upper frequencies so as to aid in the solution of the selectivity problem at the receiver. Turning to the question of the desirable frequency range in receivers, I regard an upper limit of 5 000 cycles per sec. as more practical than one of 10 000 cycles per sec. Whatever is ideally desirable, we must face the realities of the situation; these are the present state of the ether and of public demand. If the public demands to listen to foreign stations—and a strengthening of this demand is a natural consequence of the increase in the field strength from these stations—the manufacturer is obliged to face the problem of removing the present conditions of severe interference. In actual fact the frequency separation between stations is not as great as 9 kilocycles per sec., since heterodyne notes of 3 000 cycles per sec. or less are often encountered. The only hope of solving the problem of heterodyne interference lies in increasing the strength of our own side-bands; the degree of selectivity necessary to give correct response at the receiver will then at the same time reduce the level of interfering signals. With reference to " grasshopper noises," the idea, mentioned by Mr. Turner, of reducing the effective interference from the side-bands of a neighbouring station by cutting down the amplitude of the interfering signals at the detector stage and restoring the attenuated side-bands of the wanted signals by audio-frequency distortion, is very important: One must, however, bear in mind that if the higher frequencies are removed before the detector stage, when they are restored the ground noise at the detector will be accentuated. I should be interested to hear of any practical experience of this effect. If development is to proceed along the lines of this idea we shall have to consider all possible means of accentuating the upper frequencies after the detector stage, and this may prove to be an important consideration in loud-speaker design. It was interesting to hear Mr. Turner state that in comparing two systems with different cut-off frequencies it was necessary to present the two alternatives in quick succession, in order that the difference might be appreciated. This would indicate that the gain in quality of reproduction was but a slight compensation for the resultant loss of selectivity, and on this account manufacturers would be reluctant to increase the frequency range of their receivers. In my opinion we are not yet using to the best advantage the limited frequency range imposed by the present state of the ether.

Dr. W. F. Rawlinson: Problems connected with the selectivity of broadcast receivers become ever more important as the number of high-power broadcasting stations increases. Comparisons of receivers and discussion of their characteristics would be greatly facilitated if some definition of selectivity could be agreed upon. Prof. Fortescue's two figures of merit do not appear, however, to cover the whole of the problem; in fact his figure (a) giving the area of the response curve as compared with the ideal appears to have no definite meaning. Assuming the receiver under consideration to give a somewhat peaked curve; at what point does he propose to make the height of the ideal curve equal to that of the actual curve? This point, which will obviously decide the relative areas, can be varied at will. A better way of aiming at such a figure of merit would be to construct an ideal curve of rectangular form having as base a frequency range of 50 to 10 000 cycles per sec., and an area equal to that of the actual curve of the receiver between the limits of zero and 20 000 cycles per sec. (Anything above the latter frequency would be inaudible.) Counting the actual area of the receiver curve which lies within the ideal curve as positive, all areas of the receiver curve which lie outside as negative, and any area of the ideal curve not filled by the actual curve as negative; the ratio of the algebraic sum of these areas to the area of the ideal curve would be the figure of merit for the response curve as a whole. Prof. Fortescue's proposals will only give the low-frequency response curve of the receiver, and this has little to do with the selectivity. For instance, a receiver with no high-frequency circuit at all, but having a simple detector resistance coupled to the aerial and a band-pass low-frequency filter with a sharp cut-off at 50 and 10 000 cycles per sec., would give perfect results according to Prof. Fortescue's two figures of merit; yet it would be hopelessly unselective. The measurement of the sound-intensity output for a given high-frequency input may give a figure of merit applicable to the case of ordinary-type receivers used in or near London, but it is not of so much value for receivers to be used at a distance from a high-power local station. From aural observation on the South Coast it appears that the signals from Mühlacker are often 10 to 100 times as strong as those from London Regional, and at such times it is the shape

of the high-frequency resonance curve outside the ideal band which is all-important. Unless the attenuation at 9 kilocycles per sec. from the carrier frequency is greater than 100 we shall receive the carrier and one side-band of the unwanted station, and these will be received at greater strength than the programme of the wanted station, and no audio-frequency correction will get rid of the interference. The figures of merit proposed by Prof. Fortescue would not show up this defect, even with the modifications suggested. A receiver which cut down to 30 per cent at 5 000 cycles per sec. would apparently be considered satisfactory on the basis of the proposed figures of merit, yet it might prove very unselective under the conditions of reception suggested above. True selectivity must be associated with the high-frequency part of the receiver, to which any figures of merit must apply. The following is a possible way of defining two figures of merit. Plot the high-frequency resonance curve of the receiver for a continuous-wave input of constant amplitude at various frequencies. Measure the actual area within a band of $\pm$ 4 500 cycles per sec. of the frequency to which the receiver is tuned. Construct a rectangle of the same area on the base of $\pm$ 4 500 cycles per sec. about the mean frequency. The first figure of merit (*a*) depends on the maximum departure of the actual curve from the mean height, i.e. the height of the rectangle. If this is not greater than 50 per cent it will not be noticeable in the audio-frequency output. The second figure of merit (*b*) expresses the ratio of the height of the rectangle to the height of the actual resonance curve at 9 000 cycles per sec. from the mean frequency. For receivers used near London a figure (*b*) of about 10 might be good enough, but for receivers used on the South Coast this figure should be of the order of 1 000. Experience shows that moderate quality free from interference is preferable to ideal quality and another station breaking through. Since in practice the carrier waves of stations are only 9 kilocycles per sec. apart, one cannot hope to avoid interference and cross modulation if one retains frequencies much above 5 000 cycles per sec. in the transmitter output. Whilst I do not think that the loud-speaker really affects the selectivity, I cannot support the suggestion that modern types of loud-speakers have a cut-off at 2 000 cycles per sec. Modern loud-speakers are much better than Prof. Fortescue would have us believe. The questions of shock and interference due to atmospherics and tramway systems, etc., must clearly be considered in connection with selectivity problems. In obtaining high-frequency selectivity we must guard against circuits capable of maintaining free oscillations for a considerable period of time.

Mr. D. N. Corfield: The discussion of the problem of frequency range seems to centre round the question of whether in order to eliminate interference it is desirable to have a range of only 4 to 5 000 cycles per sec. and put up with poor speech. Such a frequency range will give exceedingly good " commercial " speech, but it will not give lifelike speech; a frequency range of about 8 000 cycles per sec. is necessary if the sibilants are to be reproduced properly. Such a range renders necessary some form of band-pass tuning, but this introduces difficulties because the side-bands of the interfering station will come into the band width at their full strength. On the other hand, we may use instead some form of circuit giving high selectivity, and then correct for the side-band cutting in the audio-frequency stages. Such an arrangement produces a different effect, because with a selective circuit very little interference is produced by a station whose side-band frequency is receivable but whose carrier frequency is not. The accepted explanation of this is that if there is a carrier spacing of 10 kilocycles per sec. and the receiver cuts off at 8 000 cycles per sec., a 6-kilocycle interfering signal is demodulated as 4 000 cycles per sec.; in other words, the interfering side-band becomes inverted. It is well known that the highest frequencies contain the least power, and the result is that when these become demodulated they are automatically reduced in strength, since they are inverted. If we are going to get a sufficient number of stations into the allotted wavelength range, the single-side-band system will have to be adopted, either at the transmitter or at the receiver. If it is adopted at the transmitter, all the receiving sets in use at present will have to be replaced by new ones. Alternatively, we could arrange to receive only one side-band of a double-side-band transmission by employing a quartz-crystal resonance circuit, which gives a very sharp response characteristic and can be arranged to cut off either side-band at will. This system would enable one to receive a transmission even when there was an interfering transmission working on a frequency only a few hundred cycles per sec. above or below that of the wanted station. Unfortunately this applies only to one side: if there are two interfering stations, one of slightly higher and the other of slightly lower frequency than that of the wanted station, single-side-band reception will not eliminate interference. A further difficulty which presents itself in connection with the commercial use of a band-pass tuning circuit is that variation of the wavelength tuning causes a variation in band width, and nothing short of a very complicated filter will remove this defect. If a very selective circuit is employed it is found that the shape of the resonance curve remains almost identical over the whole wavelength range, and one would therefore require about the same degree of low-frequency correction throughout. It seems to me that a low-frequency correction circuit is much more likely to remain stable when installed in a private house than is a high-frequency band-pass circuit.

Mr. F. Murphy: Prof. Fortescue emphasized the necessity for a definition of selectivity: in my opinion such a definition must depend upon the conditions to be met, as clearly if there were only one broadcasting station in the world there would be no selectivity problem. In the area where I live the field strength from Brookman's Park is about 300 mV per metre, and that from Mühlacker is 1·5 mV per metre, so that if I desire to receive signals from the latter station my receiver must have a selectivity sufficient to discriminate against the adjacent channel of a station 200 times as strong. There are three forms of interference, namely ordinary heterodyne interference, intelligible modulation interference, and side-band interference. It occurred to me to investigate whether any one form of resonance circuit would give greater freedom from interference

than any other, assuming that a certain audio-frequency response had to be obtained. Assume that one station is transmitting with a modulation depth M_1; the strength of the side-band is $\frac{1}{2}M_1$, and the response in the receiving circuit is $\frac{1}{2}M_1\theta$. Assume that the second station has a carrier strength of x units and modulation depth M_2, so that the strength of its side-band is $\frac{1}{2}M_2x$ and the response in the receiving circuit is $\frac{1}{2}M_2x\theta$. If we divide one response by the other, θ cancels out, and the ratio of the interfering side-band to the wanted side-band is M_2x/M_1. In other words, it is quite independent of the shape of the resonance curve if the same audio-frequency response is obtained. The only way of getting rid of the side-band interference is to make $\theta = 0$. I recently had occasion to investigate a system which uses a very low-decrement circuit, and I was told that in this particular system the important feature was the free vibrations set up by the applied signal. If a modulated sine wave of e.m.f. is applied to a simple resonant circuit, the resultant can be expressed by two sets of terms. One term represents the free vibration of the circuit and the others the forced vibrations. The coefficient of the free vibration term depends only on the accidental value of the applied e.m.f. at zero time of application to the circuit. This free-vibration term cannot, therefore, be a measure of the modulation. We are dependent on the other terms in exactly the same way as we are in the case of the more normally damped circuits in common use. Returning to the question of the definition of selectivity, I think this should involve three terms. The first term should define the selectivity in terms of the field strength which it would discriminate against in the adjacent channel. The second term should be a statement of the percentage audio-frequency response at, say, 4 kilocycles per sec. off tune. The third term should define the volume-level at which the tests are conducted.

Mr. H. A. Brooke: I should like to refer to the necessity for discriminating between definitions of selectivity which apply to one side of the detector stage, and those which apply to the other. The difficulty with regard to neighbouring transmissions which are capable of giving interference cannot be overcome merely by limiting the audio-frequency response, owing to the fact that cross modulation will occur in the detector itself. Selectivity must therefore be defined on the high-frequency rather than on the audio-frequency side. If interference is to be eliminated under the present conditions of a total separation of about 9 kilocycles per sec., the highest audio frequency that it is permissible to transmit and receive must necessarily be limited to about 4 500; otherwise there is always trouble due to the neighbouring side-bands.

Mr. H. L. Kirke: I recently investigated the problem of stray side-bands and the cut-off at 5 000 cycles per sec. by carrying out a test on two transmitters of frequencies separated by 9 kilocycles per sec. One was supposed to be giving the transmission which was required, and the other the interfering transmission. In the interfering-transmitter circuits I inserted an arrangement enabling me to switch in and out a filter circuit cutting off at 5 000 cycles per sec. The receiving circuits were so arranged that no programme interference was audible, but there was strong side-band interference. I found that frequencies above 5 000 in the neighbouring transmission created no interference in the receiver. Mr. Harvey Fletcher has recently published* in America curves giving the average energy to be expected in speech and music over the frequency range, and these curves show that although the human ear appreciates frequencies above 5 000 the intensities at which these frequencies are normally transmitted by musical instruments or the human voice are very low indeed. There is therefore no argument in favour of cutting off in the transmitter at 5 000 cycles per sec.; it is better to leave the higher frequencies for those people who are fortunate enough to be able to appreciate them. As regards Mr. Willans's reference to the frequency characteristics of microphones, I should like to state that the microphone we normally use has a rising frequency characteristic both above and below 1 000 cycles per sec., rising up to about 6 decibels at 4 000 to 6 000 cycles per sec. and cutting off fairly sharply above 6 000 cycles per sec. All our amplifiers have straight-line characteristics to within a decibel or so, and we are therefore sending out an excess of the audio frequencies of the order 4 000–5 000 cycles per sec. The response of an untreated condenser microphone is liable to be 15 decibels higher at 4 000 or 5 000 than it is at 1 000 cycles per sec., when one is speaking in a direct line with the microphone; in other directions the response will be lower. We have recently been experimenting in two of our studios with a new type of condenser microphone which we believe will respond to frequencies well above 10 000 cycles per sec. It has a sensibly flat frequency characteristic. Tests in our studios show that everybody can distinguish the presence of the higher audible frequencies in the output from loud-speakers of modern design. The majority of people prefer to have these frequencies present and they like the flat response given by the microphones, whatever may be the frequency characteristic of the loud-speaker. When listening with a receiver which has a cut-off before the detector of 6 decibels at 5 000 cycles per sec. and 14 at 8 000 I can tell at once whether the new type of condenser microphone is being employed. With regard to the question of stray side-bands, we have made many tests on the question of the difference between general interference and side-band interference, all of which tend to show that the shape of the frequency characteristic is the important factor. In an arrangement whereby total demodulation could be made to take place either by complete removal of the interfering carrier or by demodulation in the detector, provided our receiver had otherwise flat frequency characteristics we should expect to experience considerable side-band interference. Our tests show that this interference actually occurs. By using a circuit with a radio-frequency characteristic which can remove all frequencies above 5 000 cycles per sec. on each side of the wanted carrier, we can eliminate side-band interference. If, instead, we place immediately after the first detector a low-pass filter which cuts off at 5 000 cycles per sec., the same result will be produced. Consider the case where we obtain complete demodulation due to the use of a linear detector, the field-strength ratio of the two carriers being 10 or 12 to 1. If the difference between the carrier frequencies is 9 kilocycles

* *Bell System Technical Journal*, 1931, vol. 10, p. 349.

per sec., we have in the anode circuit of the detector a 9-kilocycle note which has the same modulation as the interfering station. The system is like the intermediate-frequency circuits of a super-heterodyne receiver. If we remove all the frequencies associated with the interference we shall experience no interference at all. If, on the other hand, we do not remove all these frequencies the interference will be audible as side-band and not as programme interference. If these currents or voltages encounter any subsequent non-linear device in the apparatus, such as a valve or a transformer, they will again be rectified as in the second detector of a super-heterodyne circuit, and whole-programme interference will be experienced. Thus one can get rid of side-band interference by cutting off after the detector. With regard to cut-off at high audio frequencies, several years ago we carried out tests with what were then considered to be the best types of loud-speakers, and we found that most people were agreed that an overall cut-off at 5 000 cycles per sec. was tolerable. They liked the higher frequencies to be included if possible, however. Very few people could notice when frequencies above 7 000 were cut off. Turning to the question of the use of highly-selective simple tuned circuits and tone compensation, I am impressed by the importance of amplitude distortion in and before the detector valve. If we use a non-linear detector we shall certainly produce distortion, resulting in the appearance of harmonics which were absent originally. The process of amplifying the higher frequencies to a greater extent than the low, exaggerates all these distortion terms. If any of the side-bands are wrongly phased or have the wrong amplitude in relation to one another, we shall also experience distortion. As an example of this, we recently tested a set made up on the principle of a super-heterodyne circuit with very sharply tuned intermediate-frequency circuits and compensation for the frequency characteristic in the low-frequency circuits. When observing frequency characteristics we noticed that an applied modulating frequency of 200 cycles per sec. produced in the loud-speaker a note whose frequency was estimated to be about 800 cycles per sec. The analysis of the output was as follows:—Fundamental frequency 1·6 per cent; 2nd harmonic 30 per cent; 3rd harmonic 9 per cent; 4th harmonic 37 per cent; etc., up to the 10th harmonic. We then proceeded to observe the high-frequency characteristics by injecting a variable-frequency carrier into the receiver and measuring the resultant rectified current. The high-frequency characteristics were found to be very asymmetrical, due to various so-called band-pass filters which had been incorporated to reduce the signal strength of the second channel, and presumably also to errors in the tuning of the intermediate-frequency circuits. The shape of the overall characteristic is important. I prefer a tail-off to a cut-off at 5 000 cycles per sec. In the design of receivers manufacturers are up against the problem of endeavouring to make a receiver which is acceptable to all sections of the public. In the first place, as Mr. Murphy suggested, some people want to receive a signal strength of $1\frac{1}{2}$ millivolts per metre when the interfering signal of an adjacent channel has a strength of 300 millivolts per metre. To do this, one must be prepared to accept a cut-off at 4 000 or 5 000 cycles per sec. in the overall characteristic. Secondly, there are those who are receiving 25, 50, and 100 millivolts per metre, and who are quite content to go on listening to their local programme. For them the problem is easy. Thirdly, there is the question of designing a type of set suitable for the people who live in areas where the signal strength is 5 or 10 millivolts per metre, and it is here that the problem of knowing where to cut off is most difficult.

Mr. H. Dewhurst: I have been asked to show a few slides of a filter (referred to by Mr. Barton) which was

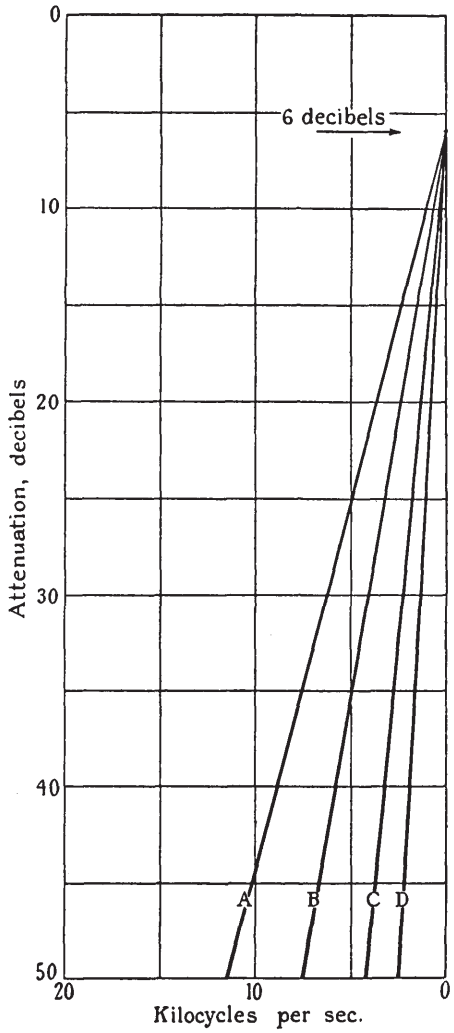

FIG. A.—Average filter slopes, reduced to 300 kilocycles per sec.

A.—180 kilocycles per sec.; slope 2·7 decibels per kilocycle.
B.—300 " " " ; slope 4·5 " " "
C.—{500 " " " (R.A.E.)} slope 8·0 " " "
{300 " " "
D.—300 " " " ; slope 13·5 decibels per kilocycle.

A, B, C, are commercial 3-element intermediate-frequency filters. D is a 4-element intermediate-frequency filter designed by the Royal Aircraft Establishment.

constructed at the Royal Aircraft Establishment, Farnborough, for use in a super-heterodyne receiver. The filter design was based on the telephone practice

developed by Zobel and Campbell in America. The first consideration in designing a filter is that of the impedance out of, or into, which it is to work. If the filter is worked at an impedance level for which it is not intended, reflection losses occur. For example, if a band-pass filter with a flat-top characteristic were used under wrong impedance conditions the flat top would degenerate into two peaks and the sides of the filter characteristic would become less steep. The only existing high-frequency filters which we knew about were of the 3-element type incorporating a tuned circuit in either the series or the shunt arm, and a condenser in the other; the usual arrangement being a coupling condenser in the series arm. Filters of this type are being used on commercial short-wave telephony and telegraphy. They are cheap to construct and are fairly easily tuned and handled. Fig. A shows the characteristic curves of various 3-element filters. Our first attempt (Filter C), also a 3-element filter, was an improvement on the existing types. A drawback of the 3-element filter, however, is that the losses in the coils modify the performance; instead of a flat top, a rounded top is obtained to the characteristic. A first essential, therefore, is to have very good coils. A further drawback is that this type gives an attenuation of a high

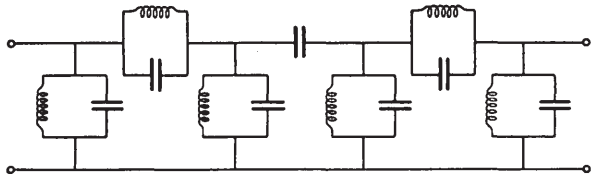

FIG. B.—Circuit of Royal Aircraft Establishment intermediate-frequency filter (D), composed of two complementary 4-element, double-M derived, π sections, and one 3-element π section.

order where it is not required. We therefore tried what is known as the " infinity cut-off " type of filter. This gives a cusp which pulls down the slope to a higher degree than would an increase in the magnification of the constituent coils. Our second design (Filter D) gives an attenuation of 34 decibels $2\frac{1}{2}$ kilocycles per sec. away from the point where the flat top starts. Thus, D would attenuate by 34 decibels an interfering signal $2\frac{1}{2}$ kilocycles per sec. away, whereas C would attenuate it by only 20 decibels. Filter D is of the 4-element type with a 2-element (see Fig. B) circuit tuned in both series and parallel arms. The series members provide the infinity cut-offs. The coils used in this filter are placed in copper cans to maintain their frequency characteristics constant and prevent interaction. Used in this way they still have a magnification of 200. The amplifier is provided with a semi-aperiodic tuned-anode coupling coil; and there are three contacts which automatically connect up the filter as soon as this is dropped into position.

Mr. C. E. G. Bailey: Experiments with a highly selective receiver incorporating audio-frequency correction show that this arrangement has certain advantages. If in order to correct the high-frequency cut-off we put in a resonance circuit to obtain the last iota of correction, the audio- and radio-frequency responses alike will drop after the selected upper frequency limit, and the consequent overall cut-off will be very steep. Accordingly, these circuits can eliminate that type of interference where the side-bands of the two transmissions do not overlap. Interference of the type where the side-bands do overlap can only be eliminated with the help of the demodulation effect. As has been pointed out, 2 carriers, each with a pair of side-bands, produce in the detector 27 components, some assisting and others tending to neutralize each other. The demodulation effect consists in the counteracting of certain components present in the output of the detector. It is clear that if a receiver with a sharp response curve is capable of receiving single-side-band telephony, it is also capable of responding to the note produced by the carrier or one of the side-bands of an interfering wave. How does such a receiver discriminate between these two? As Mr. Turner pointed out, in the first case there is only one side-band, whereas in the second there are two. It is easy to see that if we injected single side-band telephony signals into such a receiver we should get some sort of response: but the solution is to be found, I think, in the fact that we still get the carrier and, to a certain extent, the remoter side-band of the unwanted station, and demodulation balances out certain audio-frequency components produced by the two unwanted side-bands. This can be confirmed experimentally by the fact that if to a selective circuit one adds additional circuits, thus making a band-pass system which cuts off very rapidly, interference may increase. This may account for the selectivity of receivers of the quartz-crystal type, which, apart from the tremendous increase in response near the resonant frequency, behave as rather poor single-circuit receivers. I know of no way of eliminating that type of interference where both sets of side-bands overlap both carrier waves. Mr. Willans mentioned the effects of noise in connection with corrected receivers. One of the startling characteristics of this system is the decrease in the noise background. I account for this effect in the following way. If we imagine the noise spectrum to consist of a number of components spaced at unit intervals, the noise-level is produced partly by the interference of the carrier with each component and partly by the interference of the components among themselves. A perfectly level amplifier would give a noise response due to the latter cause proportional to $N!$, but in the case of a sharply-tuned amplifier there is little cross-heterodyning between the noise components, so that this source of noise disappears. Selective receivers employing resonant audio-frequency circuits for correction suffer from phase distortion at the upper frequencies, and, in the limit, resonance of long duration may occur round about the 4 000-cycle region. This type of distortion condemns resonated audio-frequency correctors as a method of obtaining quality with selectivity. Finally, we need a definition of selectivity. Since demonstration effects are complicated it is advisable to base this on the simplest considerations, and I suggest that selectivity should be defined in terms of the degree of mistuning in kilocycles per sec. which is required to reduce the signal level of a wave by 40 decibels. In order to avoid the logical confusion of using a term which is greater when the number describing it is less, I propose to name this

quantity the " connivance " of the receiver and not the "selectivity."

Mr. G. Builder: A question relating to receiver design which has been very little discussed is the distortion of transient modulation in tuned circuits of low decrement. In this connection some interesting effects may occur in band-pass filters having a double-peak resonance characteristic. The effect of the double peak is to superimpose a damped low-frequency oscillation on the original transient modulation; this oscillation may be regarded as a surging of energy between the coupled circuits of the band-pass filter. The dependence of the superimposed frequency on the separation of the resonance peaks may be readily confirmed by experiment. The effect may also be considered to be due to the combination of two transients set up at the resonant frequencies, and it may equally well be interpreted in terms of side-bands. I should like to point out that in the case of sinusoidal modulation, if one employs a band-pass circuit in which the ratio between the gain at the side-band frequencies to that at the carrier, multiplied by the modulation ratio, is greater than unity, serious distortion (chiefly second-harmonic) is introduced into the modulation. I have given these particular examples, not because they are directly relevant to the subject of selectivity, but in order to show that we must consider the possibilities of distortion of the transient modulation when designing circuits of low decrement.

Mr. T. Wadsworth: While there is little doubt that a certain degree of selectivity must be allowed, the real criterion of a receiver from the user's point of view should be the quality of the output which it delivers. From what has been said by the previous speakers it seems to me that there are two schools of thought regarding this question of selectivity and quality. The first school regards the quality of the receiver as its essential characteristic, and Mr. Ashbridge's remarks have shown that the B.B.C. belongs to this school. The second school regards the receiver as an extremely selective device, and considers that the quality which can be achieved at present is good enough for broadcast reception. We are of opinion that the first school is right. It follows as a corollary that we must regard the present frequency separation, 9 kilocycles per sec., as inadequate, because with this separation one can only get 4 500 cycles per sec. of audio-frequency range. The second school favours ultra-selective circuits and the use of tone control. It is questionable whether this method is fundamentally correct, because there is no evidence that by the use of tone control one can reinstate something which has already been taken away in order to provide increased selectivity. In connection with the B.B.C. transmissions, it would be an advantage to know the frequency characteristics of all the stations. Contrary to Mr. Turner's opinion, we have recently recorded on a film frequencies up to 7 000 or 8 000, and have found these films, both on speech and on music, to be of better quality than the average broadcast reception. We have also made a loud-speaker which has a response at 9 000 cycles per sec. and have found by experiment that the presence of this high frequency in the reproduction is beneficial, particularly in connection with speech.

Mr. W. J. Brown (*communicated*): It has been adequately demonstrated that the upper limit of the audio-frequency response of a sensitive receiver is approximately half the kilocycle spacing of adjacent broadcasting stations. With the present 9-kilocycle separation of stations the highest audio-frequency permissible is therefore 4 500 cycles per sec. It is not to be expected that any real improvement will be obtained by merely extending the station spacing to 11 or 12 kilocycles per sec. (with a corresponding maximum audio frequency of 5 500 or 6 000 cycles per sec.), since the increase in range would be much less than an octave in the musical scale. To produce any real effect at least a full octave should be added, which involves one of two alternatives, either (*a*) increasing the broadcast station spacing to 18 kilocycles per sec., which involves halving the number of stations; or (*b*) enforcing the suppression of one side-band from every broadcasting station, leaving the carrier and a single side-band to be transmitted. Transmission of a single side-band only has been rightly condemned, as it necessitates a special homodyne receiver; but a carrier and single side-band can, of course, be received on any normal receiving apparatus. Such a transmission would have the additional advantage of reducing the harmonic distortion in reception. When two side-bands and a carrier are received, even the best of detectors cannot avoid the introduction of a double-frequency component due to the beating of the two side-bands with each other. The elimination of one side-band from the transmission would eliminate this double-frequency component.

Prof. C. L. Fortescue (*in reply*): The outstanding feature of this discussion is the unanimity of opinion in favour of an extension of the audio-frequency range amongst those speakers who have had the opportunity of carrying out careful comparisons. Mr. Ashbridge and Mr. Kirke, Mr. Turner and Mr. Wadsworth, Mr. Corfield and others, all advocate extension up to 8 000 or even 10 000 cycles per sec. One or two speakers advocate a limitation to 5 000 cycles per sec., but apparently only on the grounds of unavoidable compromise. The feasibility of this extension of range with the present separation of carrier waves by 9 000 cycles per sec. has not been fully debated. Mr. Turner, Mr. Barton, Mr. Cohen and others envisage very complicated receivers; Mr. Corfield and Mr. Brown advocate single-side-band working in spite of the difficulties mentioned by Mr. Ashbridge and in my opening remarks. Mr. Bailey appears to favour very highly selective circuits combined with tone correction, but other speakers express doubts with respect to this system. Several speakers, and particularly Mr. Scroggie, point out the remarkable results already obtained with the small separation of carrier waves now used, the explanation being, no doubt, that given by Mr. Kirke and others, viz. that the energy in the high-frequency audio components is small. The advantage to be gained by linear detectors has been mentioned by Mr. Turner, Mr. Kirke and Mr. Bailey, but without making the matter very clear. That a strong carrier on an adjacent wavelength but not giving audible beats will almost blot out an incoming programme is certain; but when this carrier is modulated and when side-bands of both transmissions beat audibly with both

carriers the situation is quite different and far more complicated. The analysis is laborious but favours the view that in this case there is no immunity from interference to be obtained by a straight-line rectifier. The final conclusion appears to be that the greater perfection of rendering resulting from an extension of the audio-frequency range can only be obtained by increasing the separation of carriers. Actual experience must, of course, be the final arbiter, and it is unfortunate that so few people have actually heard the results obtainable by extension up to a frequency of 8 000.

An important question of design has been raised by Dr. Rawlinson in claiming that true selectivity must reside in the high-frequency stages of the receiver. It is obvious, of course, that if both the carrier and a side-band of an interfering programme are received on the high-frequency side, no selectivity on the audio-frequency side can have any effect. Provided, however, that the carrier of the interfering programme is eliminated in the high-frequency stages, it certainly becomes possible to eliminate very high beat notes either in the audio-frequency stage or even in the acoustical conversion in the loud-speaker. The essential point is that the beating of interfering side-bands shall not produce an audible note within the desired range of audibility.

One of the most important points raised in my opening remarks is the ability of the non-technical general public to handle a very selective receiver. Mr. Turner has alluded to the difficulties experienced, but several other speakers advocating complicated receivers seem to have omitted this aspect entirely. The situation has changed enormously in this respect during the last few years on account of the introduction of " ganging " of the controls. Provided that this ganging is sufficiently accurate, the public can probably be trusted to make a delicate adjustment with the accuracy necessary to give a good result. It is only necessary to watch an entirely non-technical person adjusting a receiver having ganged tuning and reaction control to realize the skill that is acquired in the course of a very brief experience. But in spite of this it seems very doubtful whether a receiver having more than two delicate adjustments would meet with public approval.

Finally there is the point raised by Mr. Willans of the non-linearity of the B.B.C. transmissions and the effects which this must have on the shape to be given to response curve of the ideal receiver. The present over-accentuation of the frequencies between 4 000 and 6 000 is almost certainly valuable with most of the more commonly used receivers, owing to the falling-off of their curves in this range. If this falling-off were not common there would probably be a great outcry against the action of the B.B.C. and an urgent demand for linear transmission characteristics!